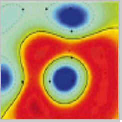

Protocol Inspection and State Machine Analysis (PRISMA)

Tammo Krueger
Hugo Gascon
Konrad Rieck

Protocol Inspection and State Machine Analysis (PRISMA)

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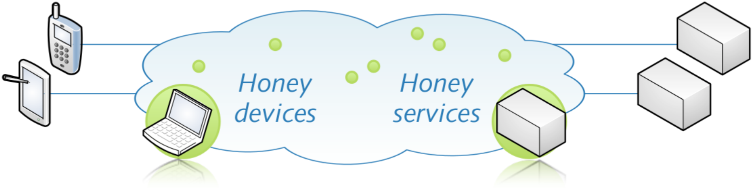
19.6.2012 University of Göttingen

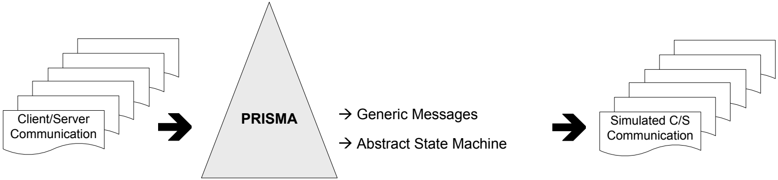
Proactive Security for Convergent Communication (PROSEC)



Proactive protection of services:

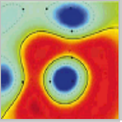
- Self-learning protocol analysis
- Deployment of “Honey-Services”
- Proactive protection of communication and attack detection

Motivation

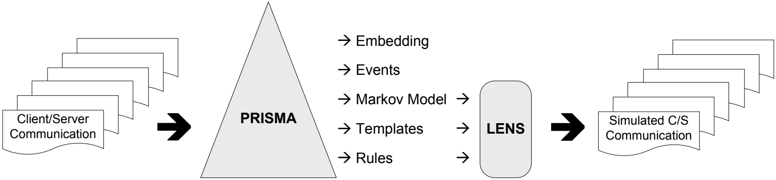


Given a pool of client/server communication infer generic messages and abstract state machine

1. To emulate services (honeypots)
2. Lure attackers
3. Gather information about threat potential



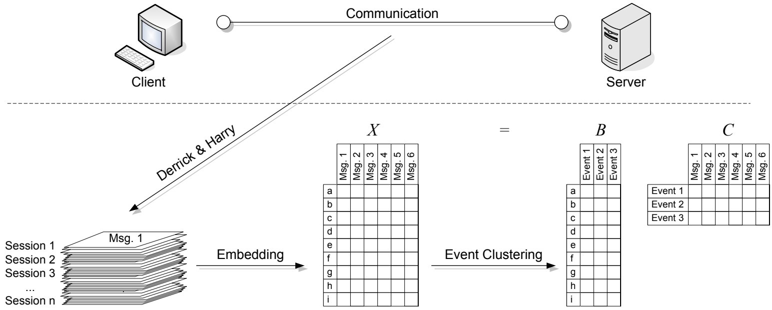
Motivation – Top-Down Model of Tasks

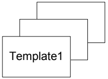


By embedding and event clustering approximate abstract state machine and message types:

- Infer *Markov model* of the behavior
- Find inherent structure of the messages (*templates*)
- Gather information flow between states (*rules*)

System Overview



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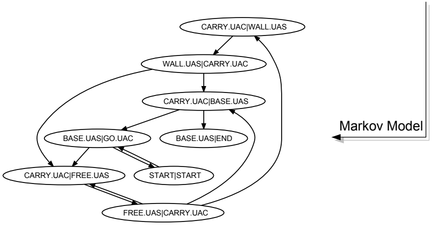
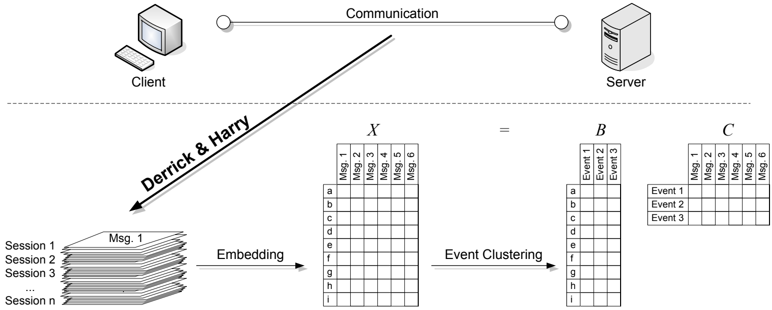
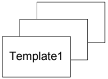
RULE srcField:3 dstField:1 type:ExactRule
RULE dstField:4 type:DataRule
data:678537408252460955, ...
RULE dstField:5 type:DataRule
data:252460957,252461242,252461608, ...
RULE dstField:6 type:DataRule
data:12004,12020,12018,12028,12002,12004
```



System Overview – Preprocessing



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data:12004,12020,12018,12028,12002,12004
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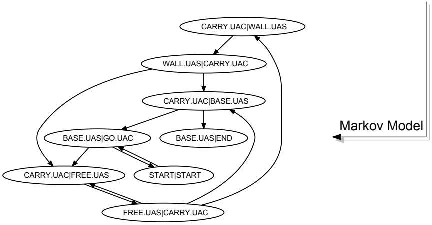


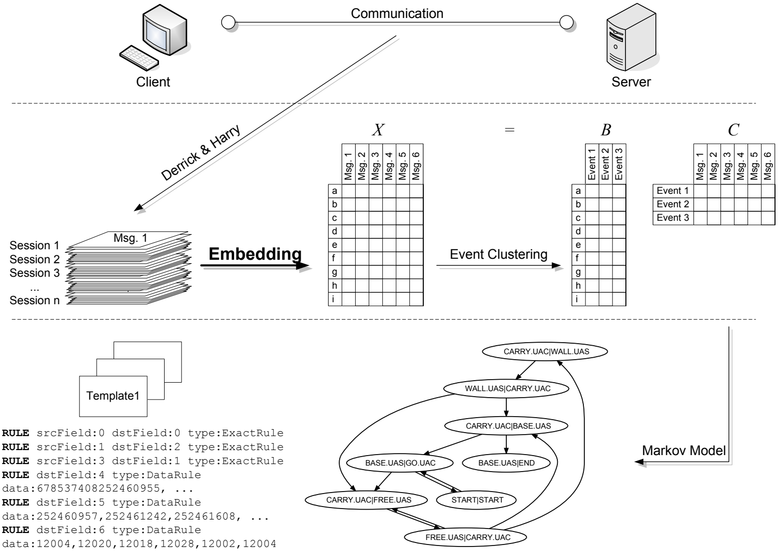
Preprocessing

- Data acquisition via `tcpdump`
- Tool chain needed, to process these binary dump files

  Derrick assembles packet contents based on the mature `libnids` library

  Harry concatenates packets to messages and extracts session information
- Data available for the next steps:
  1. messages as sequence of bytes
  2. sessions as sequence of messages
- Point 1 will be used in the *embedding* step
- Outcome of the *embedding* step will be used in the *clustering* step
- Point 2 and outcome of the *clustering* will be used in the *model building* step

System Overview – Embedding



Embedding

1. **N-grams:** Given the set of all possible n-grams over byte sequences $S = \{0, \dots, 255\}^n$, we define the embedding function $\phi : \{0, \dots, 255\}^\star \mapsto \mathbb{R}^{|S|}$ as

$$\phi(x) = (\phi_s(x))_{s \in S} \quad \text{with} \quad \phi_s(x) = \mathrm{occ}_s(x).$$

   Example ($n = 3$):

$$\phi(\text{"Hello"}) = (0, \dots, \overset{\text{Hel}}{1}, \overset{\text{ell}}{1}, \overset{\text{llo}}{1}, \dots, 0)^T \in \mathbb{R}^{16777216}$$

2. **Tokens:** Given a set of seperators *Sep* we can split the byte sequence into tokens; example ($Sep = \{␣\}$):

$$\phi(\text{"We'll meet again"}) = (0, \dots, \overset{\text{We'll}}{1}, \overset{\text{meet}}{1}, \overset{\text{again}}{1}, \dots, 0)^T \in \mathbb{R}^?$$

Dimension Reduction via Statistical Testing

- Embedding space high-dimensional but sparse
- Some dimension do not carry real information:
  - Fixed *protocol* tokens
  - Random, *volatile* tokens (cookies, nonces, ...)
- Focus the analysis by splitting the feature set F:

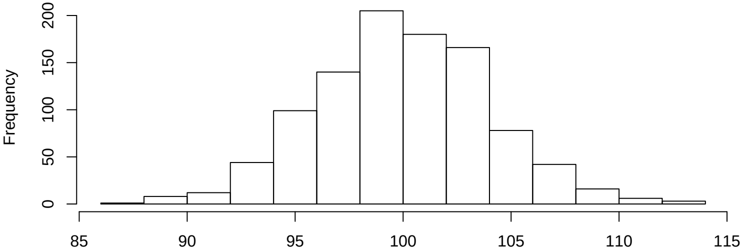
$$F = F_{protocol} \cup F_{alphabet} \cup F_{volatile}$$

- Keep features, which are not part of the protocol **and** are not volatile
- How to decide, whether a feature belongs to $F_{protocol}$ or $F_{volatile}$? Use **statistical testing!**

Anatomy of a Statistical Testing Procedure

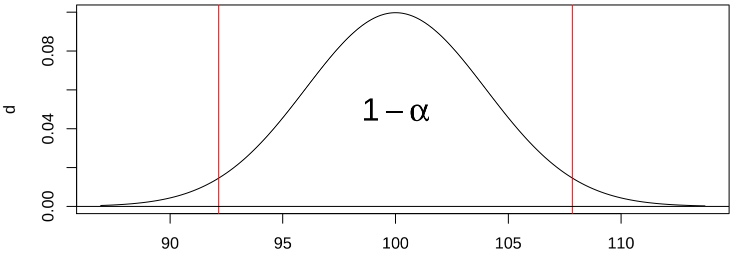
- Given measurements decide, whether we can accept or reject a hypotheses (H_0) in favor to an alternative (H_1) in a statistical sense
- Distribution assumption (parametric/non-parametric)
- Predefined significance level ($\alpha \in 0.01, 0.05, 0.1$)
- Test statistic
- p-value: probability to observe a value for the test statistic at least as extreme as the value that was actually observed given H_0 is true
- Decision rule: reject H_0 if p-value is smaller than the significance level

Statistical Test – Example I



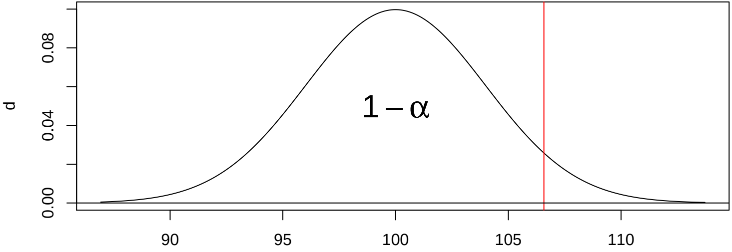
- Measure impact of fertilizer A on grain shaft size:
  1. collect N samples from several fields treated with fertilizer A
  2. record the mean size of these N samples per field
  3. plot the distribution and calculate mean μ_A and standard deviation σ_A
- Outcome: $\mu_A = 100cm, \sigma_A = 4cm$

Statistical Test – Example I



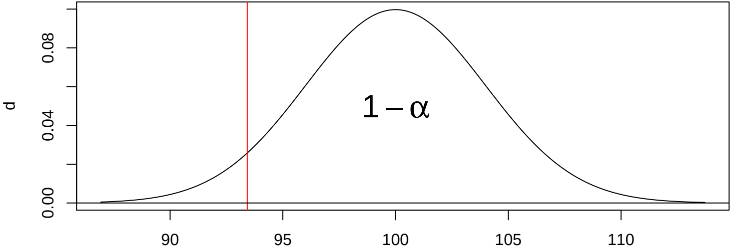
- Given a new measurement of a field x, can we determine with a given error level of α, whether it was treated with fertilizer A?
- Assume normal distribution $\rightarrow (1-\alpha) = 95\%$ of the data lies in the interval $[92.16, 107.83]$!

Statistical Test – Example I



- Different question: has new field x a bigger grain shaft size than the fields treated with fertilizer A?
- Assume normal distribution $\rightarrow (1-\alpha) = 95\%$ of the data lies in the interval $[-\infty, 106.57]$!

Statistical Test – Example I



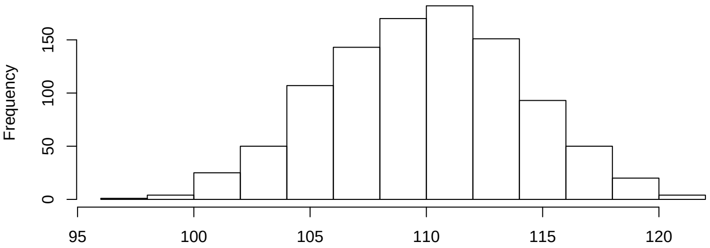
- Different question: has new field x a smaller grain shaft size than the fields treated with fertilizer A?
- Assume normal distribution → $(1-\alpha) = 95\%$ of the data lies in the interval $[93.42, +\infty]$!

Statistical Testing: What Can Go Wrong?

	H_0 is true	H_1 is true
Accept H_0	Right decision	Type II Error (β)
Reject H_0	Type I Error (α)	Right decision

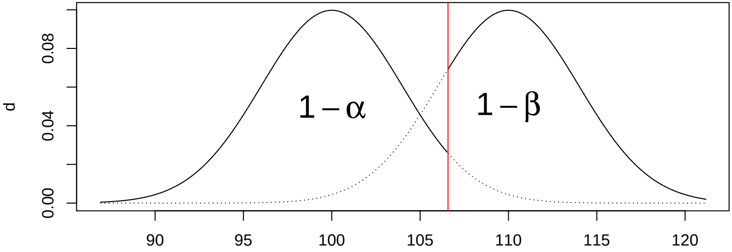
- Type I error controlled by *significance level* α
- Type II error is used to describe the *power* $(1 - \beta)$, i.e. the probability of correctly rejecting H_0

Statistical Test – Example II



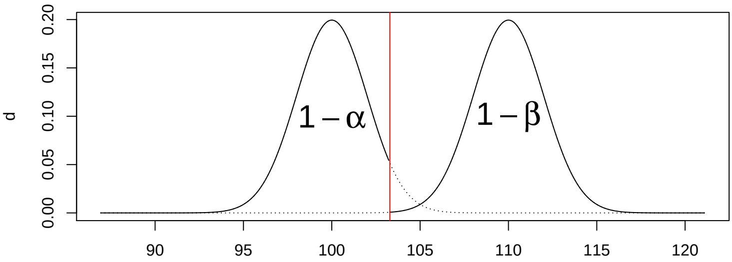
- Measure impact of new fertilizer B on grain shaft size:
  1. collect N samples from several fields treated with fertilizer B
  2. record the mean size of these N samples per field
  3. plot the distribution and calculate mean μ_B and standard deviation σ_B
- Outcome: $\mu_B = 110cm, \sigma_B = 4cm$

Statistical Test – Example II



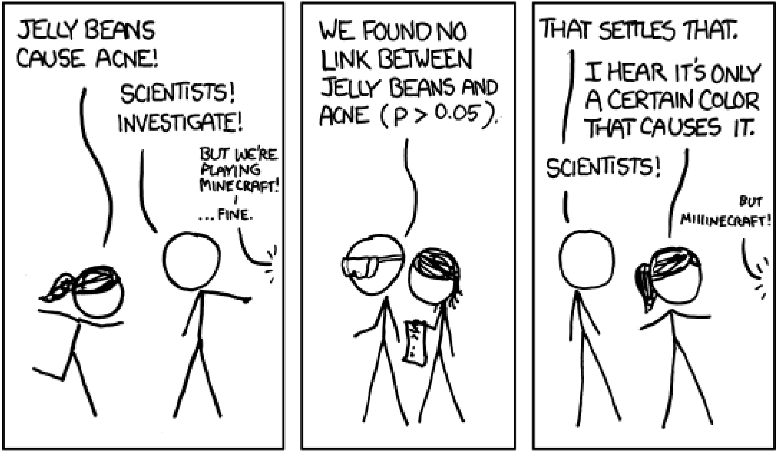
- Different question: has new field x been treated with fertilizer A or fertilizer B?
- Power $1 - \beta$ of test is directly connected to the significance level α!

Statistical Test – Example II



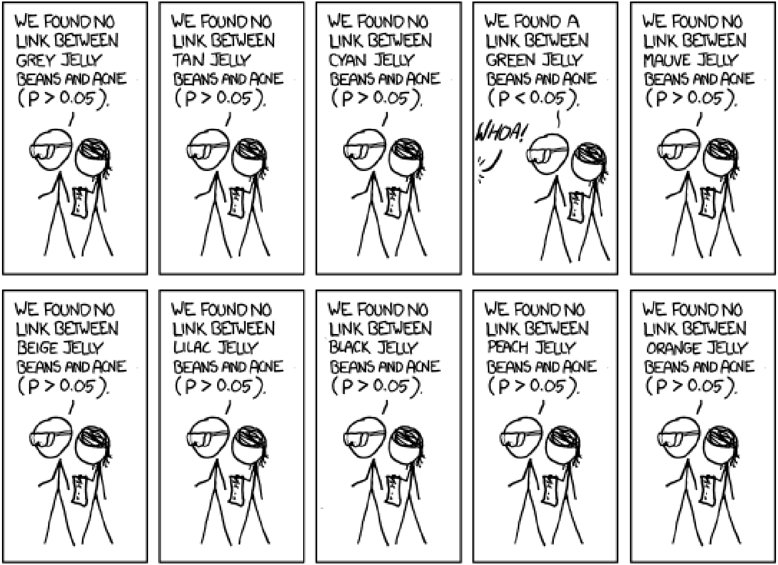
- How can we improve the power of the test?
- Increase the sample size N to lower the standard deviations σ_A and σ_B!

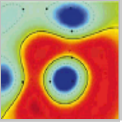
Statistical Testing: What Can Go Wrong? – Part 2



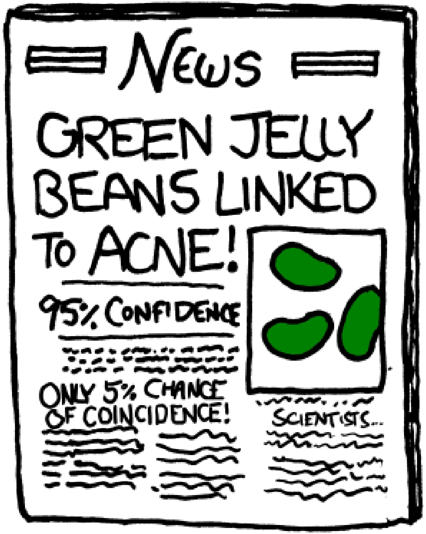
http://xkcd.com/882/

Statistical Testing: What Can Go Wrong? – Part 2

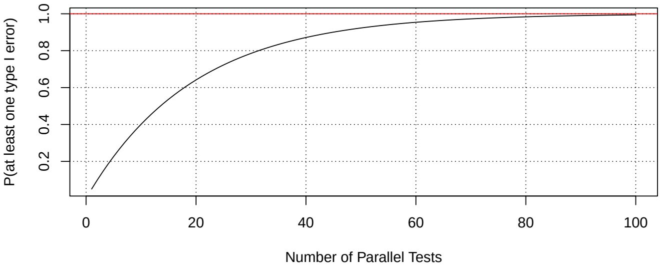




Statistical Testing: What Can Go Wrong? – Part 2



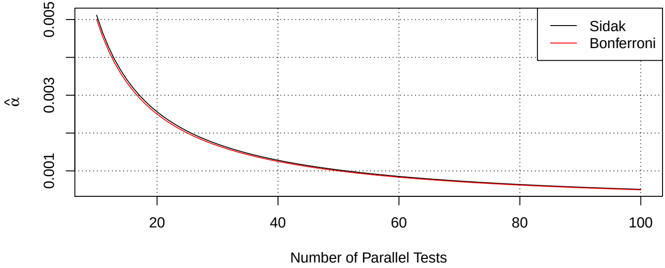
Multiple Testing



- In explorative data studies (e.g. micro-array experiments) a lot of tests are made in parallel
- For each of these k tests an error of type I can occur with probability α:

$$
\begin{aligned}
& P(\text{at least one type I error}) \\
= \quad & 1 - P(\text{no type I error}) \\
= \quad & 1 - (1-\alpha)^k
\end{aligned}
$$

Multiple Testing – α Correction



- Use adjusted $\hat{\alpha}$ (Sidak Correction):

$$
\begin{aligned}
& P(\text{at least one type I error}) = \alpha \\
\longleftrightarrow \quad & 1 - (1 - \hat{\alpha})^k = \alpha \\
\longleftrightarrow \quad & \hat{\alpha} = 1 - (1 - \alpha)^{1/k}
\end{aligned}
$$

- Bonferroni Correction: use $\hat{\alpha} = \alpha/k \approx 1 - (1 - \alpha)^{1/k}$.

Dimension Reduction via Statistical Testing

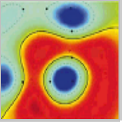
- Embedding space high-dimensional but sparse
- Some dimension do not carry real information:
  - Fixed *protocol* tokens
  - Random, *volatile* tokens (cookies, nonces, ...)
- Focus the analysis by splitting the feature set F:

$$F = F_{protocol} \cup F_{alphabet} \cup F_{volatile}$$

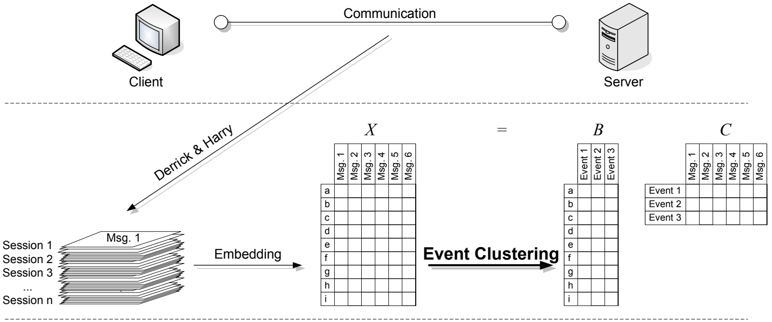
- Calculate frequency f of each feature and test via aproximated binomial test:

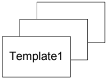
$$\begin{aligned} p_{protocol} &= binom.test(H_0 : f \approx 1.0) \\ p_{volatile} &= binom.test(H_0 : f \approx 0.0) \end{aligned}$$

- Adjust significance level α for multiple testing
- Keep features, which are not part of the protocol **and** are not volatile: $p_{protocol} \leqslant \hat{\alpha} \wedge p_{volatile} \leqslant \hat{\alpha}$



System Overview – Event Clustering



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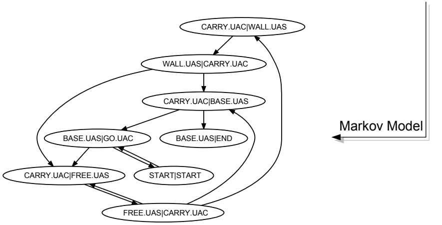
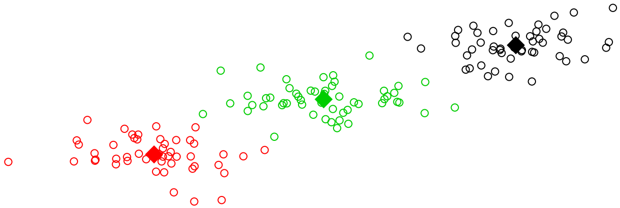
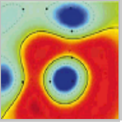


Clustering – Introduction



- Vectorial representation of messages allows application of geometrical concepts
- Example k-means: find k cluster *centers*, which exhibit the minimal squared *distance* to their assigned observations
- Other methods from machine learning readily applicable



Event Clustering – Application in PRISMA

- Clustering as factorization of embedding matrix $X \in \mathbb{R}^{k,N}$ with $B \in \mathbb{R}^{k,e}$, $C \in \mathbb{R}^{e,N}$, $b_i \in \mathbb{R}^{k,1}$, $c_i \in \mathbb{R}^{e,1}$, $\underline{e \ll k}$:

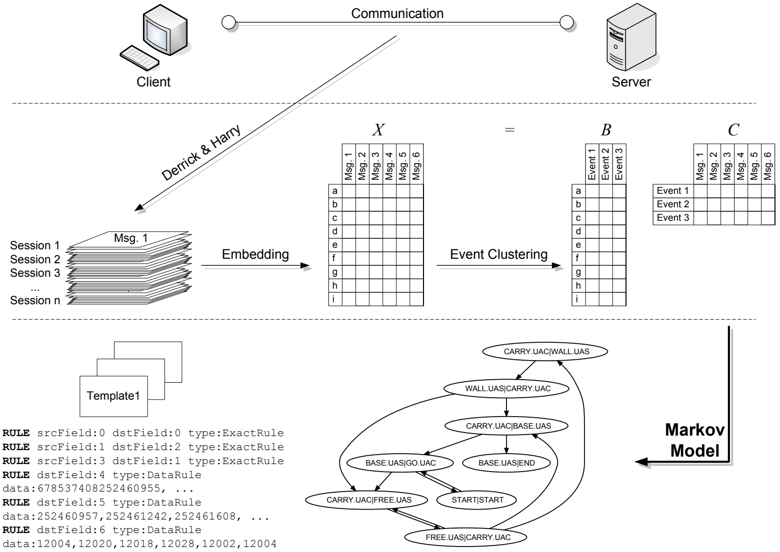
$$X \approx BC = \overbrace{\begin{bmatrix} b_1 & \dots & b_e \end{bmatrix}}^{\text{event basis}} \underbrace{\begin{bmatrix} c_1 & \dots & c_N \end{bmatrix}}_{\text{event assignments}}$$

  via *Non-Negative Matrix Factorization*:

$$\begin{aligned}(B, C) \quad &= \quad \operatorname*{arg\,min}_{B,C} \|X - BC\| \\ & \quad\quad \text{s.t. } b_{ij} \geqslant 0,\ c_{jn} \geqslant 0\,.\end{aligned}$$

- Other techniques (e.g. hierarchical clustering, expert knowledge) can be incorporated easily

System Overview – Markov Model



Markov Model – Introduction

- Probabilistic model to describe process evolving over time
- Formally, the process is a sequence of random variables:

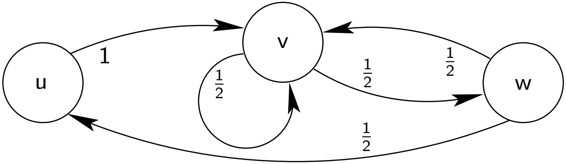
$$S_1^T = [S(1), S(2), \ldots, S(T-1), S(T)]$$

- ... which fullfill the *Markov Assumption*:

$$\forall t \in 1, \ldots, T : P_{S(t)|S(1),S(2),\ldots,S(t-2),S(t-1)} = P_{S(t)|S(t-1)}.$$

- $S(i)$ represents the internal state of the system
- Examples and notation from *Hidden Markov Models and Dynamical Systems* by Andrew M. Fraser (SIAM, 2008)

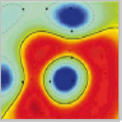
Markov Model – Example



$$P_{S(1)} = \left[\tfrac{1}{3}, \quad \tfrac{1}{3}, \quad \tfrac{1}{3}\right], \tag{1}$$

$P(s(t+1) \mid s(t))$		$S(t+1)$ u	v	w
$S(t)$	u	0	1	0
	v	0	$\frac{1}{2}$	$\frac{1}{2}$
	w	$\frac{1}{2}$	$\frac{1}{2}$	0

(2)



Markov Model – Example

- Calculate the probability of $s_1^4 = [u, v, w, v]$:

$$
\begin{aligned}
P(u, v, w, v) &= P(v|u, v, w) \cdot P(w|u, v) \cdot P(v|u) \cdot P(u) && (3) \\
&= P(v|w) \cdot P(w|v) \cdot P(v|u) \cdot P(u) && (4) \\
&= \frac{1}{2} \cdot \frac{1}{2} \cdot 1 \cdot \frac{1}{3} = \frac{1}{12}. && (5)
\end{aligned}
$$

- Eqn. (3): Conditional probability ($P_{A,B} = P_{B|A} P_A$)
- Eqn. (4): *Markov assumption*
- Eqn. (5): Eqn. (1) and Eqn. (2)
- General case for s_1^T:

$$
\begin{aligned}
P(s_1^T) &= P(s(1)) \prod_{\tau=2}^{T} P(s(\tau)|s_1^{\tau-1}) \\
&= P(s(1)) \prod_{\tau=2}^{T} P(s(\tau)|s(\tau-1))
\end{aligned}
$$

Hidden Markov Model – Introduction

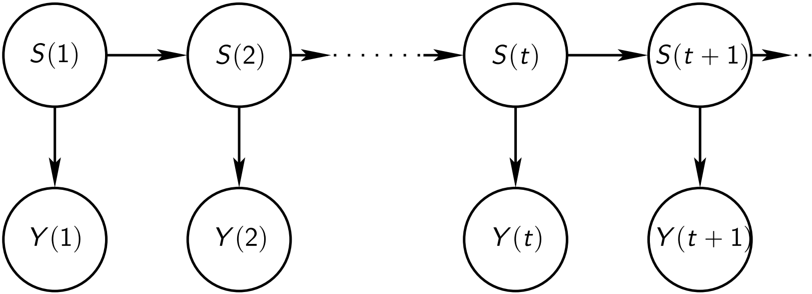
- Again, the process is a sequence of (unobservable) random variables $S_1^T = [S(1), S(2), \dots, S(T-1), S(T)]$, which generate a sequence of random variable $Y_1^T = [Y(1), Y(2), \dots, Y(T-1), Y(T)]$
- The observations are just dependent on the current *hidden* state:

$$P_{Y(t)|S_1^t, Y_1^{t-1}} = P_{Y(t)|S(t)}. \tag{6}$$

- The *hidden* state sequence is generated according to the *Markov assumption*:

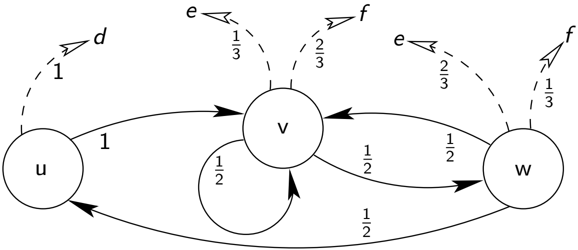
$$P_{S(t+1)|S_1^t, Y_1^t} = P_{S(t+1)|S(t)}. \tag{7}$$

Hidden Markov Model – Introduction



- Hidden Markov model as a Bayes' net
- Edges indicate dependence relations, i.e. for all $t \in 1, \ldots, T$:
  - $Y(t)$ just depends on $S(t)$
  - $S(t)$ just depends on $S(t-1)$

Hidden Markov Model – Example



		Y		
	$P(y\|s)$	d	e	f
	u	1	0	0
S	v	0	$\frac{1}{3}$	$\frac{2}{3}$
	w	0	$\frac{2}{3}$	$\frac{1}{3}$

Hidden Markov Model – Example

- Calculate the probability $y_1^4 = [d, e, f, e]$
- Possible state sequences, which could generate the observation: $[u, v, v, v]$, $[u, v, v, w]$, and $[u, v, w, v]$

s_1^4	$P(s_1^4)$	$P(y_1^4 \mid s_1^4)$	$P(y_1^4, s_1^4)$
$uvvv$	$\frac{1}{3} \cdot 1 \cdot \frac{1}{2} \cdot \frac{1}{2}$	$1 \cdot \frac{1}{3} \cdot \frac{2}{3} \cdot \frac{1}{3}$	$\frac{2}{324}$
$uvvw$	$\frac{1}{3} \cdot 1 \cdot \frac{1}{2} \cdot \frac{1}{2}$	$1 \cdot \frac{1}{3} \cdot \frac{2}{3} \cdot \frac{2}{3}$	$\frac{4}{324}$
$uvwv$	$\frac{1}{3} \cdot 1 \cdot \frac{1}{2} \cdot \frac{1}{2}$	$1 \cdot \frac{1}{3} \cdot \frac{1}{3} \cdot \frac{1}{3}$	$\frac{1}{324}$

- Now:

$$P(y_1^4) = \sum_{s_1^4} P(y_1^4, s_1^4) = \sum_{s_1^4} P(y_1^4 | s_1^4) P(s_1^4) = \frac{2+4+1}{324}.$$

Hidden Markov Model – Example

Assumptions of Eqn. (6) and Eqn. (7):

$$P(s_1^T) = P(S(1)) \prod_{t=2}^{T} P(s(t)|s(t-1))$$

$$P(y_1^T|s_1^T) = \prod_{t=1}^{T} P(y(t)|s(t))$$

Single calculation:

$$\begin{aligned} P(y_1^T, s_1^T) &= P(s_1^T)\, P(y_1^T|s_1^T) \\ &= P(s(1)) \prod_{t=2}^{T} P(s(t)|s(t-1)) \prod_{t=1}^{T} P(y(t)|s(t)). \end{aligned}$$

Iterate over all possible state sequences:

$$P(y_1^T) = \sum_{s_1^T \in S^T} P(y_1^T, s_1^T)$$

Hidden Markov Model – Algorithms

- **The Viterbi Algorithm:** Given a model θ and a sequence of observations y_1^T, finds the most probable state sequence $\hat{s}_1^T$:

$$\hat{s}_1^T = \arg\max_{s_1^T} P\left(s_1^T | y_1^T, \theta\right)$$

- **The Baum-Welch Algorithm:** Given a sequence of observations y_1^T and an initial set of model parameters θ_0, calculates a new set of parameters θ_1 that has higher likelihood:

$$P\left(y_1^T | \theta_1\right) \geqslant P\left(y_1^T | \theta_0\right)$$

Hidden Markov Model – Viterbi Algorithm

- Find the *best* sequence $\hat{s}_1^T$ that maximizes the probability $P\left(s_1^T | y_1^T\right)$
- Equivalent to maximizing $\log\left(P\left(y_1^T, s_1^T\right)\right)$, since $P(y_1^T)$ is just a constant:

$$\begin{aligned}
\hat{s}_1^T &\equiv \arg\max_{s_1^T} P(s_1^T | y_1^T) \\
&= \arg\max_{s_1^T} \left(P(s_1^T | y_1^T) \cdot P(y_1^T)\right) \\
&= \arg\max_{s_1^T} \left(P(y_1^T, s_1^T)\right).
\end{aligned}$$

- Trick for numerical stability: use log

Hidden Markov Model – Viterbi Algorithm: Definitions

$$
\begin{aligned}
u(s_1^t) \quad & \text{Utility of state sequence } s_1^t \\
& \equiv \log\left(P(y_1^t, s_1^t)\right) \\
\nu(s,t) \quad & \text{Utility of best sequence ending with } s(t) = s \\
& \equiv \max_{s_1^t : s(t) = s} u(s_1^t) \\
\omega(s, s', t) \quad & \text{Utility of best sequence with } s(t-1), s(t) = s, s' \\
& \equiv \max_{s_1^t : s(t-1) = s \wedge s(t) = s'} u(s_1^t) \\
B(s', t) \quad & \text{Best predecessor state given } s(t) = s' \\
& \equiv \arg\max_{s} \omega(s, s', t)
\end{aligned}
$$

Hidden Markov Model – Viterbi Algorithm: Overview

- *Initialize* utility $\log\left(P_{Y(1),S(1)}\left(y(1), s\right)\right)$ for each state $s \in \mathcal{S}$.
- *Forward step:* for each successive time step $t : 1 < t \leqslant T$
  - for each state s determine the best predecessor for that state and store it in $B(s, t)$
  - calculate utility of the best state sequence ending in that state and store it in $\nu(s, t)$
- *Backtrack step:*
  - identify the best final state as $\hat{s}(T) = \arg\max_s \nu(s, T)$
  - for t from $T - 1$ to 1 backtrack through B array to find the other states in the sequence $\hat{s}_1^T$, i.e., $\hat{s}(t) = B(\hat{s}(t+1), t+1)$

Hidden Markov Model – Viterbi Algorithm: Iteration

Initialize:

for each s

$$\nu_{\text{next}}(s) = \log\left(P_{Y(1),S(1)}\left(y(1), s\right)\right)$$

Iterate:

for t from 2 to T

$$\#\ \nu_{\text{old}}(\cdot) = \nu(\cdot, t-1); \nu_{\text{next}}(\cdot) = \nu(\cdot, t)$$

$$\nu_{\text{old}} = \nu_{\text{next}}$$

for each s_{next}

for each s_{old}

$$\omega(s_{\text{old}}, s_{\text{next}}) = \nu_{\text{old}}(s_{\text{old}}) + \log\left(P(s_{\text{next}}|s_{\text{old}})\right) + \log\left(P(y(t)|s_{\text{next}})\right)$$

\# Find best predecessor

$$B(s_{\text{next}}, t) = \arg\max_{s_{\text{old}}} \omega(s_{\text{old}}, s_{\text{next}})$$

\# Update ν

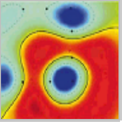
$$\nu_{\text{next}}(s_{\text{next}}) = \omega(B(s_{\text{next}}, t), s_{\text{next}})$$

Hidden Markov Model – Viterbi Algorithm: Backtrack

Backtrack:

$\bar{s} = \arg\max_s \nu_{\text{next}}(s)$
$\hat{s}(T) = \bar{s}$
for t from $T-1$ to 1
    $\bar{s} = B(\bar{s}, t+1)$
    $\hat{s}(t) = \bar{s}$

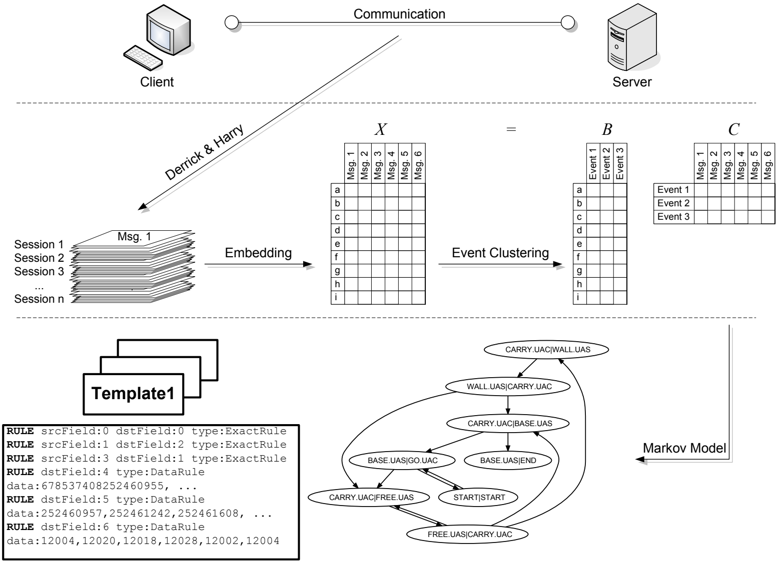
- A lot more to learn about Markov models:
  - forward/backward algorithm
  - Baum-Welch algorithm
  - Kalman filter
- So consult: *Hidden Markov Models and Dynamical Systems* by Andrew M. Fraser (SIAM, 2008)



Markov Model – Application in PRISMA

- Each message is assigned to an *event* from the event space E, so a session $S = [e_1, e_2, \ldots e_{|S|}], e_{1,2,\ldots,|S|} \in E$
- Represent the dynamics for the system by a Markov model of order $m \geqslant 2$:
  1. Estimate the frequencies of the initial events (i.e. $P(e), e \in E$)
  2. Estimate the frequencies of an event given the m predecessors in time (i.e. $P(e_t | e_{t-m}, \ldots, e_{t-2}, e_{t-1})$)
- Resulting networks can be big (potentially $|E|^m$ nodes):
  - Markov model can be transformed in a DFA
  - Compress structure via DFA minimization algorithm
- Reduced network can be described by a *hidden* Markov model

System Overview – Templates and Rules



Templates and Rules

	State A	State B	State C
Session 1	`GO 1`	`OBJECT A`	`CARRY A 0`
Session 2	`GO 2`	`OBJECT D`	`CARRY D 0`
	⋮	⋮	⋮
Session n	`GO 0`	`OBJECT B`	`CARRY B 0`
Template	`GO` $\square$	`OBJECT` $\square$	`CARRY` $\square$ `0`

- Template generation:
  - Assign each message to its corresponding state
  - Align messages and find static and changing parts (*fields*)
- Rules between templates:

Exact	copy the content of one field
Sequence	increment the number of a field
CopyCompl.	copy field and add parts before/after
CopyPartial	copy parts of the field
Data	pick a value from a data pool

Demo – Robot example

- Goal: *learn* the control of a robot, which collects goods inside a contaminated room, from network traffic
- The robot communicates with the environment by a simple protocol:
  - GO <dir>
  - CARRY <object> <dir>
- The environment responds with the following status messages after each action of the robot:
  - WALL
  - FREE
  - BASE
  - OBJECT <object>
- Hands-on example...

Demo – Robot example

Protocol Inspection and State Machine Analysis (PRISMA)

Tammo Krueger
Hugo Gascon
Konrad Rieck

Motivation

PRISMA

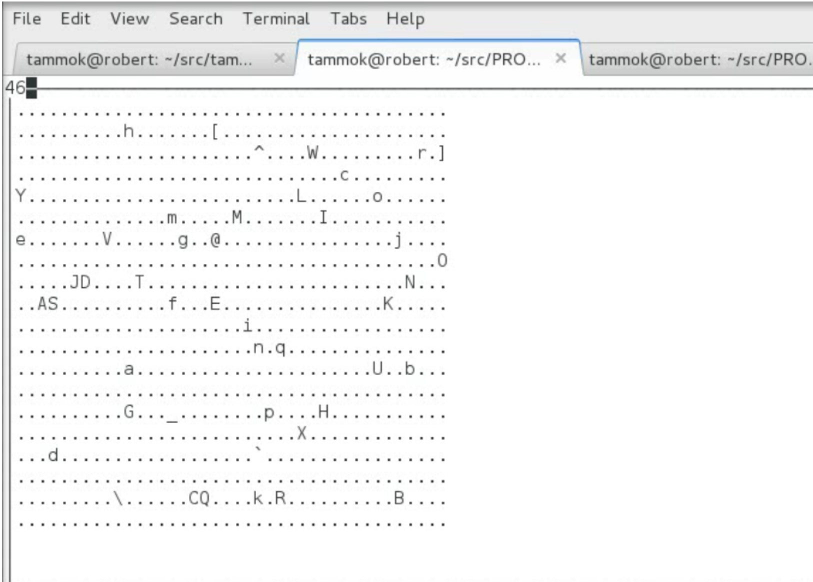
- Preprocessing
- Embedding
- Testing
- Event Clustering
- Markov Model
- Templates and Rules

Example

Evaluation

- Similarity
- Syntax & Semantic

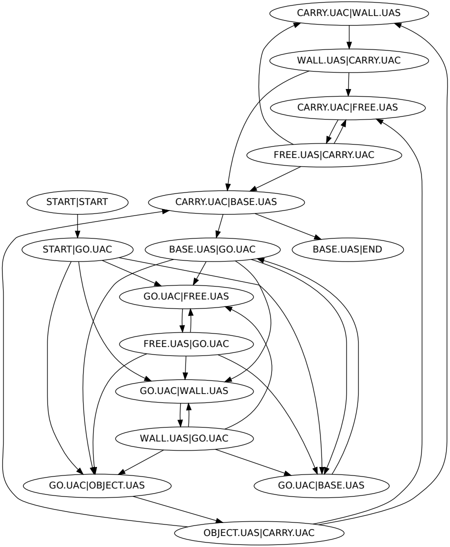
Outlook



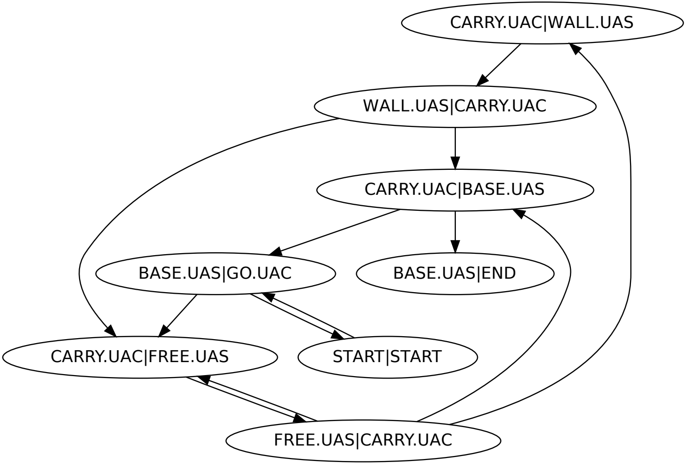
Demo – Robot example


```
GO 2 |
WALL |
GO 0 |
OBJECT E |
CARRY E 0 |
FREE |
CARRY E 0 |
WALL |
CARRY E 3 |
FREE |
CARRY E 3 |
FREE |
CARRY E 3 |
BASE |
GO 0 |
```

Demo – Robot Model before Minimization



Demo – Robot Model after Minimization



Demo – Robot Templates and Rules

TEMPLATE id:2 state:FREE.UAS—CARRY.UAC
`CARRY` □ □

TEMPLATE id:5 state:CARRY.UAC—FREE.UAS
`FREE`

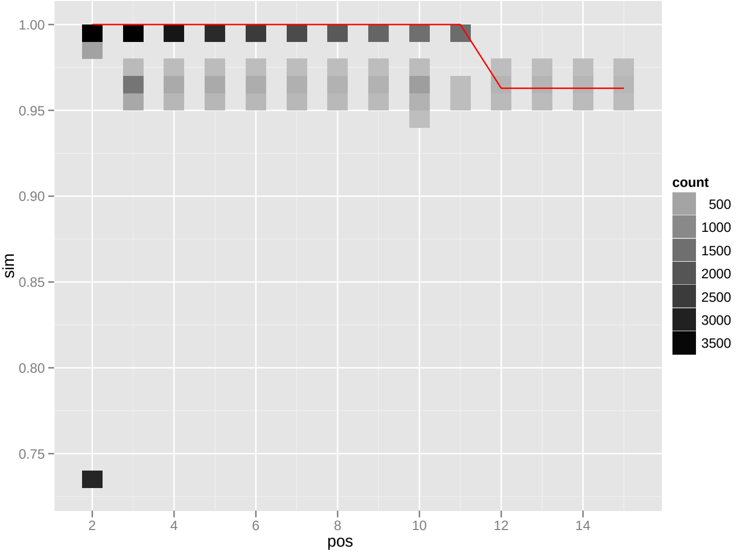
RULE transition:2;5;2
srcId:2 srcField:0 dstField:0

RULE transition:2;5;2
srcId:2 srcField:1 dstField:1

Evaluation

- Split pool into train (90% of the sessions) and testing slice
- For each session in the testing slice simulate both from the perspective of Client and Server (repeat 100 times)
- Message similarity evaluation: for each session and repetition
  1. calculate the normalized edit distance of the generated message to the real message
  2. collect all distances $\geqslant 0$ attained at a specific position
- Syntactical and semantical correctness evaluation:
  1. is message well-formed according to the underlying protocol specification (`wireshark`)
  2. is session information retained, i.e. `CallID`, `from`- and `to`-tag are preserved

Evaluation – Similarity
Alcatel-Lucent (8878 Messages)



Evaluation – Syntax & Semantic Alcatel-Lucent (8878 Messages)

	Syntax		Semantic	
	1 s. Sim.	2 s. Sim.	1 s. Sim.	2 s. Sim.
some Errors	0.03%	0.80%	3.77%	0.00%
100% Correct	99.97%	99.20%	96.23%	100.00%

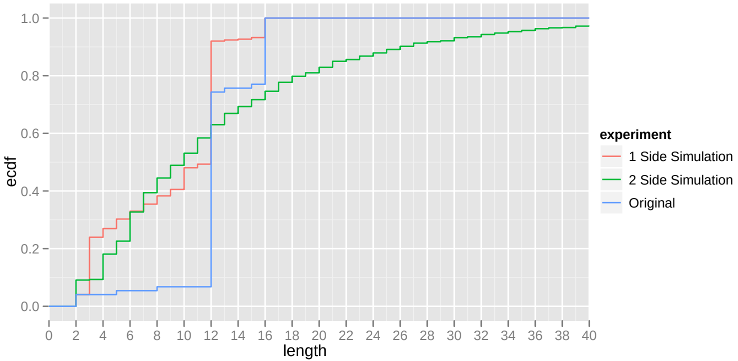
- Measure the number of correct messages per session
- **1 s. Sim.**: Simulate one side of the communication with a PRISMA model and use other side from data set
- **2 s. Sim.**: Simulate both sides of the communication with a PRISMA model

Conclusion and Future Work

- Protocol Inspection and State Machine Analysis:
  1. Embed messages in a suitable vector space
  2. Transform sequences of messages to a sequence of *events*
  3. Learn the event machine with a *Markov model*
- Application as “Honey-Service”
- Future work:
  - Stateful anomaly detection
  - Deep fuzzing
  - Infiltration of botnets

Questions? Remarks?
Thanks for your attention!

Evaluation – Length



Evaluation – Syntax & Semantic detailed Alcatel-Lucent (8878 Messages)

	Syntax		Semantic	
	1 Side Sim.	2 Side Sim.	1 Side Sim.	2 Side Sim.
$< 80\%$	0.01%	0.50%	0.30%	0.00%
$8X\%$	0.00%	0.20%	1.64%	0.00%
$9X\%$	0.02%	0.10%	1.83%	0.00%
100%	99.97%	99.20%	96.23%	100.00%

- Measure the frequency of % correct messages per session
- Reading example: For the one side simulation 0.02% of the sessions have between 90% and 99% syntactical correct messages inside the session and 99.97% of the sessions have all messages syntactical correct